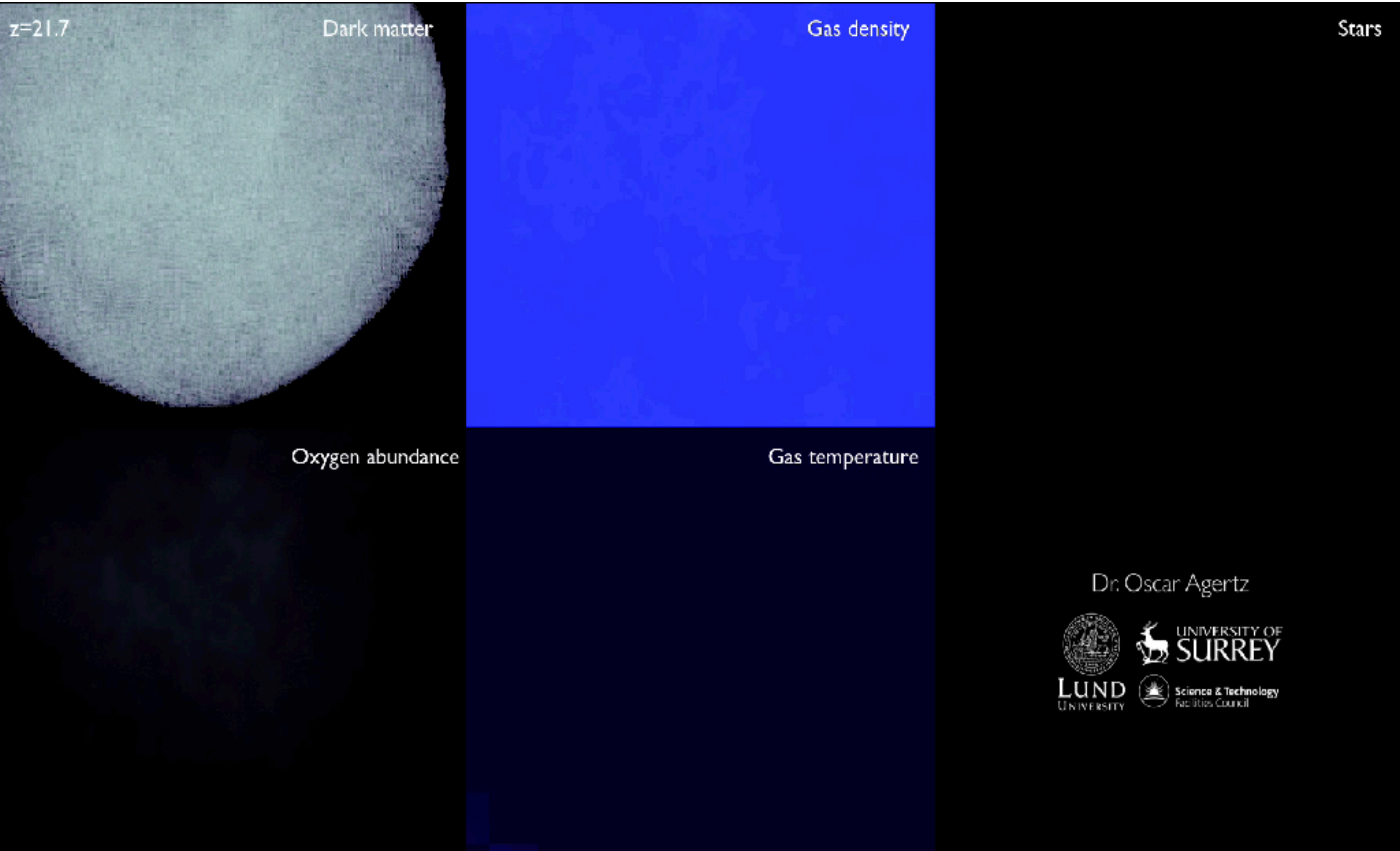
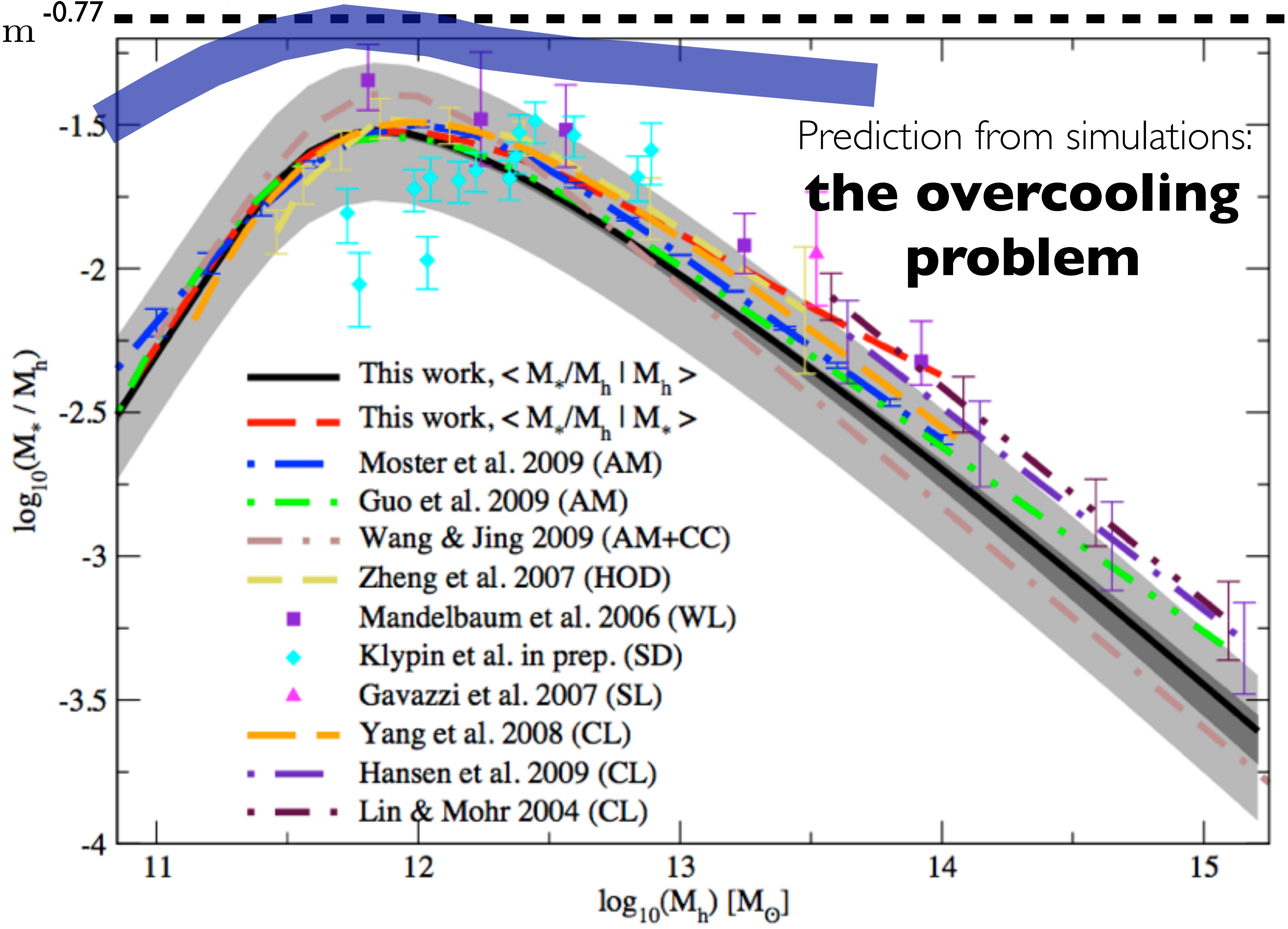
Exercise 3: Galactic outflows

Oscar Agertz (Lund University) & Jon Ramsey (Starplan/Niel Bohr Institute)



What makes galaxy formation so inefficient?

$$\frac{\Omega_{\rm bar}}{\Omega_{\rm m}} \approx 17\,\%$$

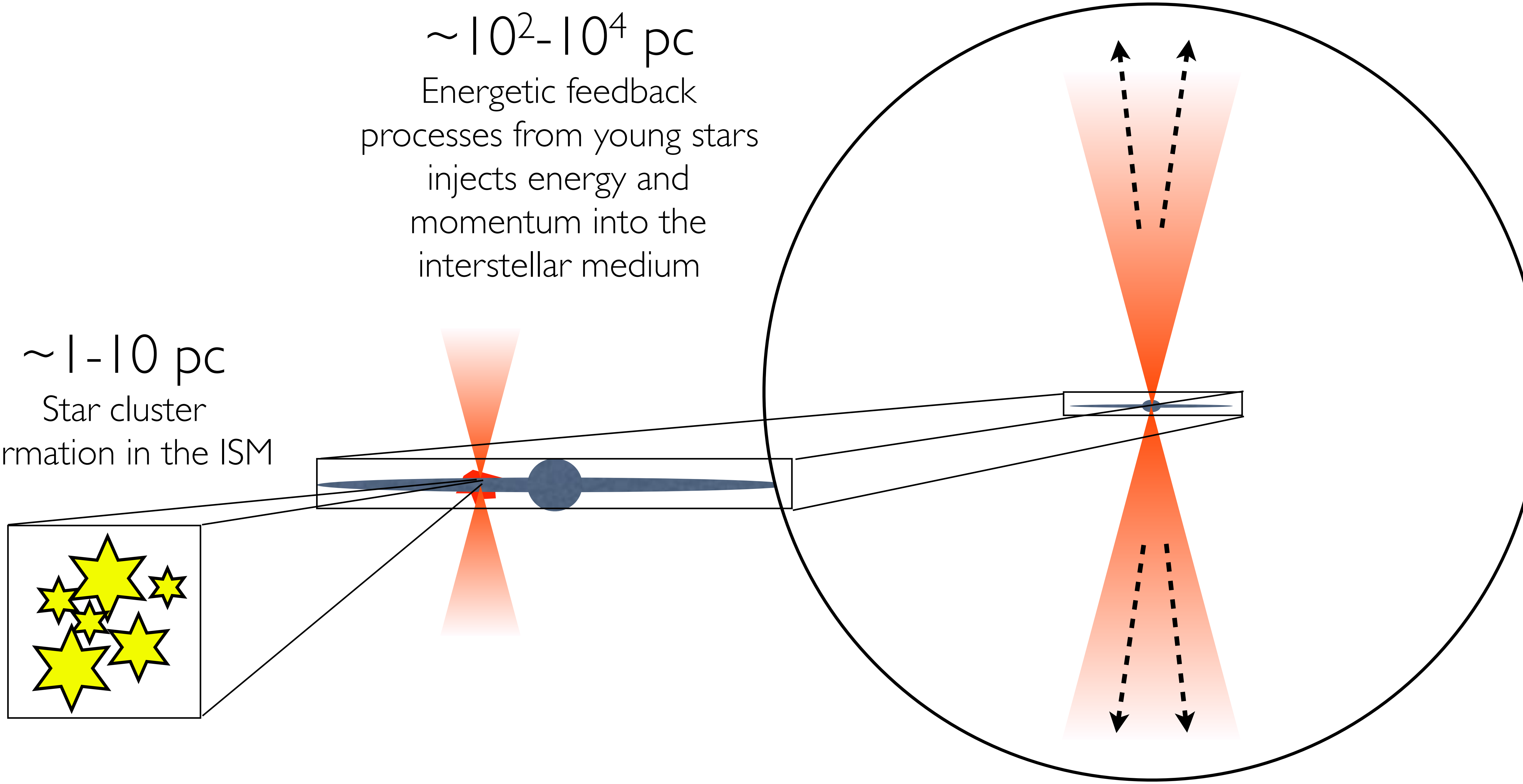


Prediction from simulations:

the overcooling problem

Possible solution: stellar feedback - galactic outflows

Connect the physics on >6 orders of magnitude in scale



~10^5-10^6 pc

In cases of vigorous star formation, gas will break out of the galaxy and escape into the halo and beyond

~10^2-10^4 pc

Energetic feedback processes from young stars injects energy and momentum into the interstellar medium

~1-10 pc

Star cluster formation in the ISM

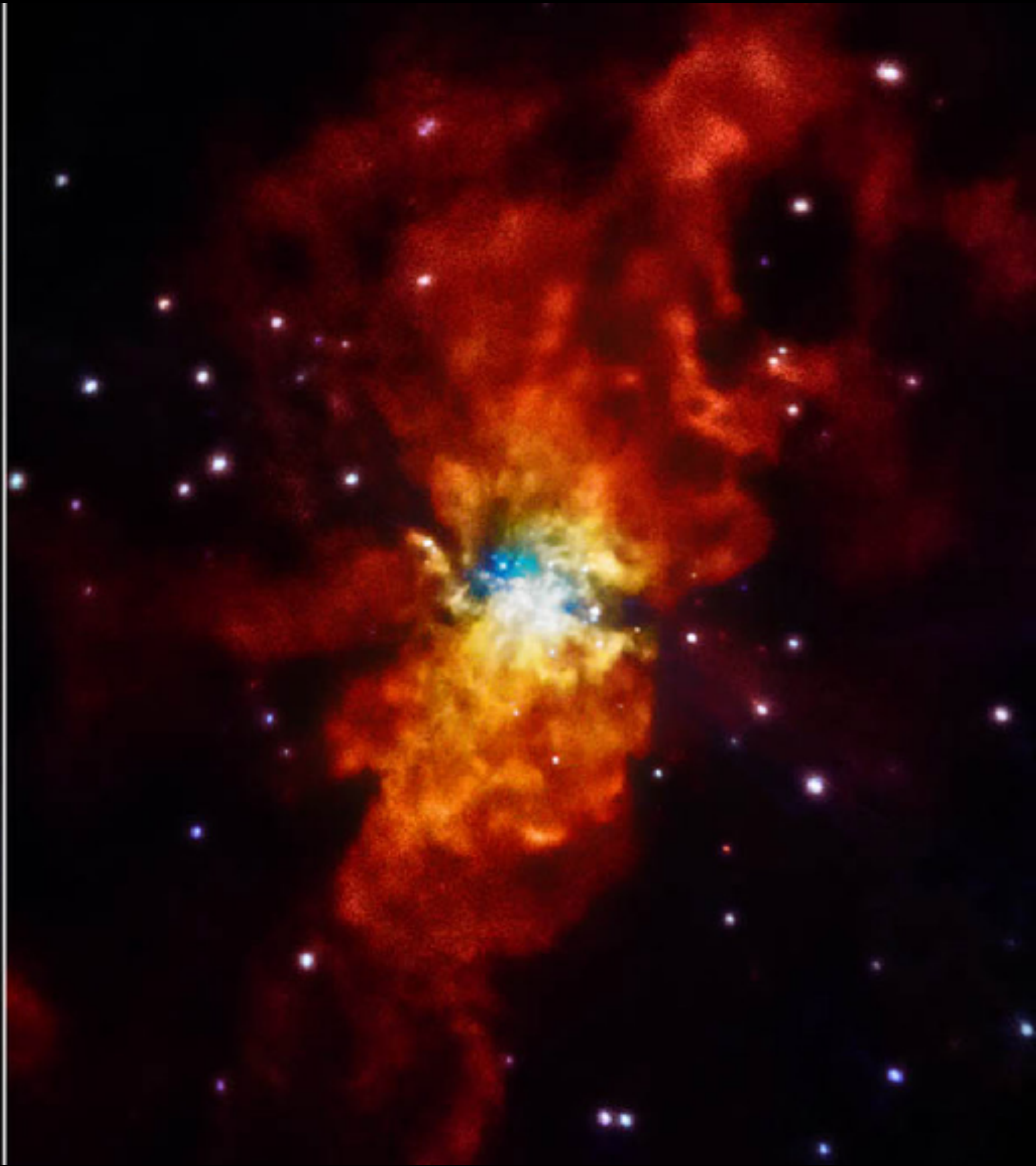
Feedback revisited

H-alpha + Optical
(Westmoquette et al., 2004)

M82: the prototypical star-burst galaxy

- Gas temperatures from $T \sim 10\text{-}10^8$ K
- Cold/warm gas (10^4 K) is embedded in a hot wind
- Outflow velocities depend on the density and temperature of the gas, with hot gas moving at >1000s km/s.

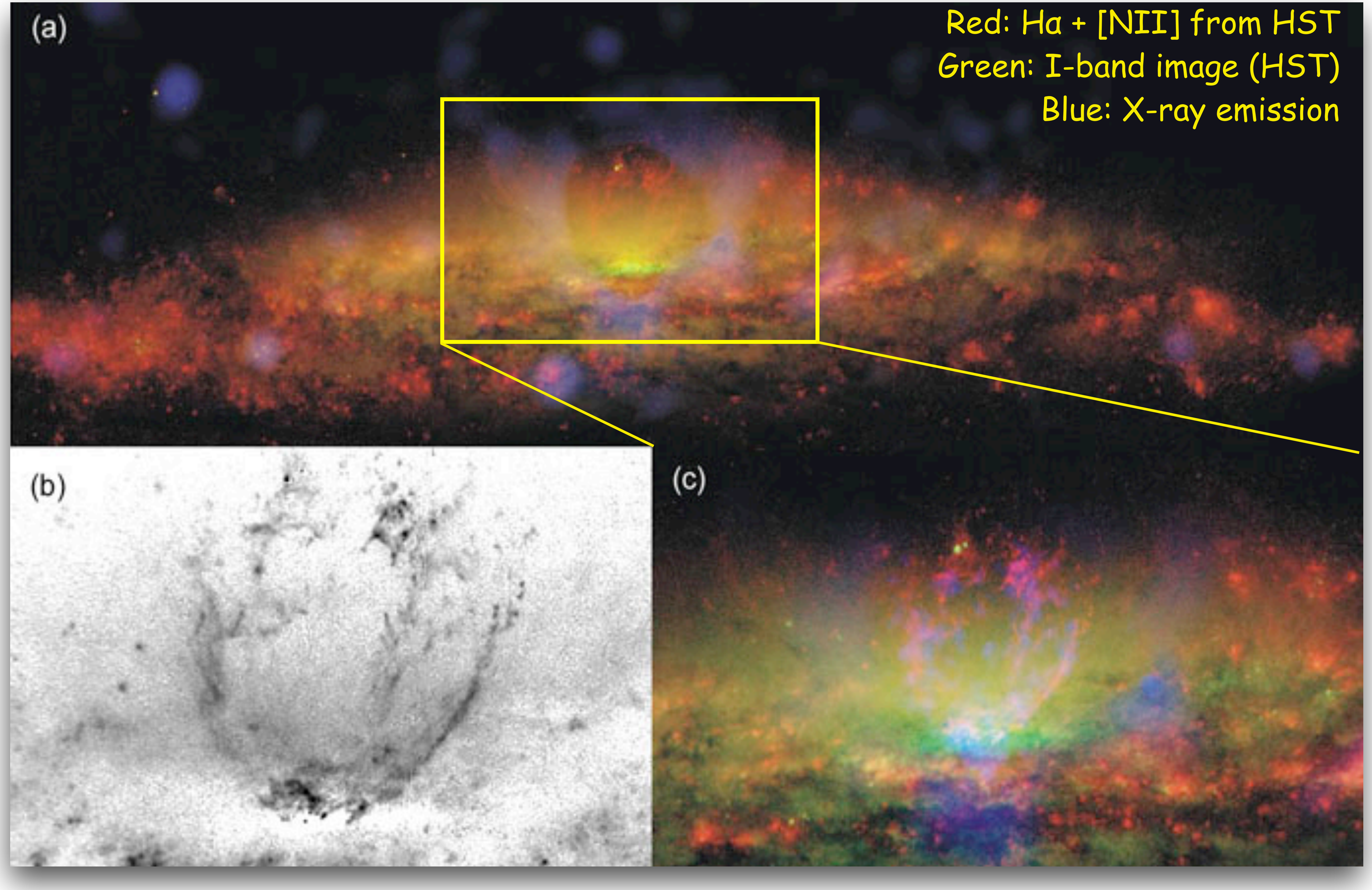
Visible light (cold/warm gas)



X-ray (hot gas)

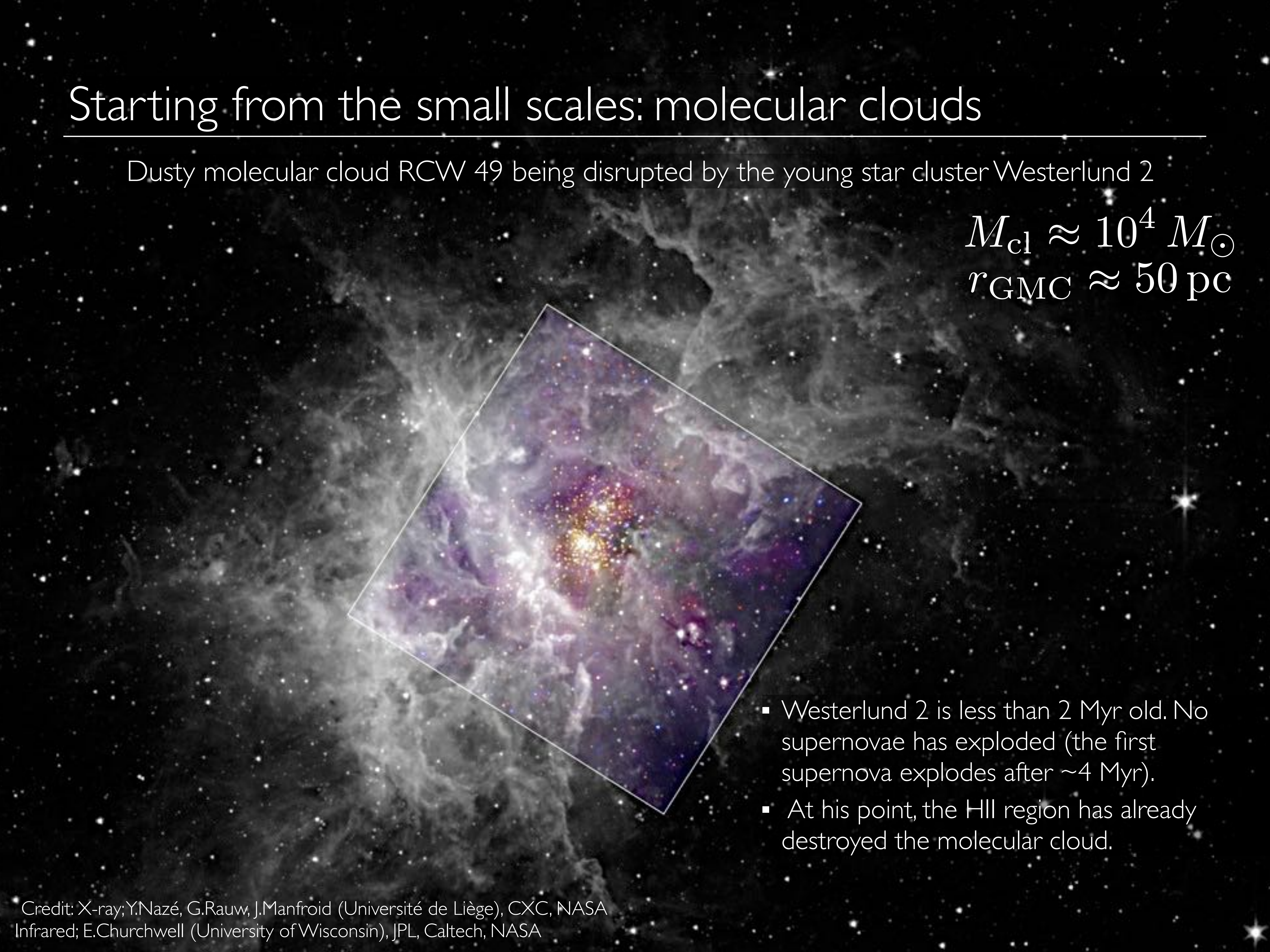
Stellar feeback and galactic winds

NGC 3079: a starbursting dwarf



Red: Hα + [NII] from HST
Green: I-band image (HST)
Blue: X-ray emission

Starting from the small scales: molecular clouds



Dusty molecular cloud RCW 49 being disrupted by the young star cluster Westerlund 2

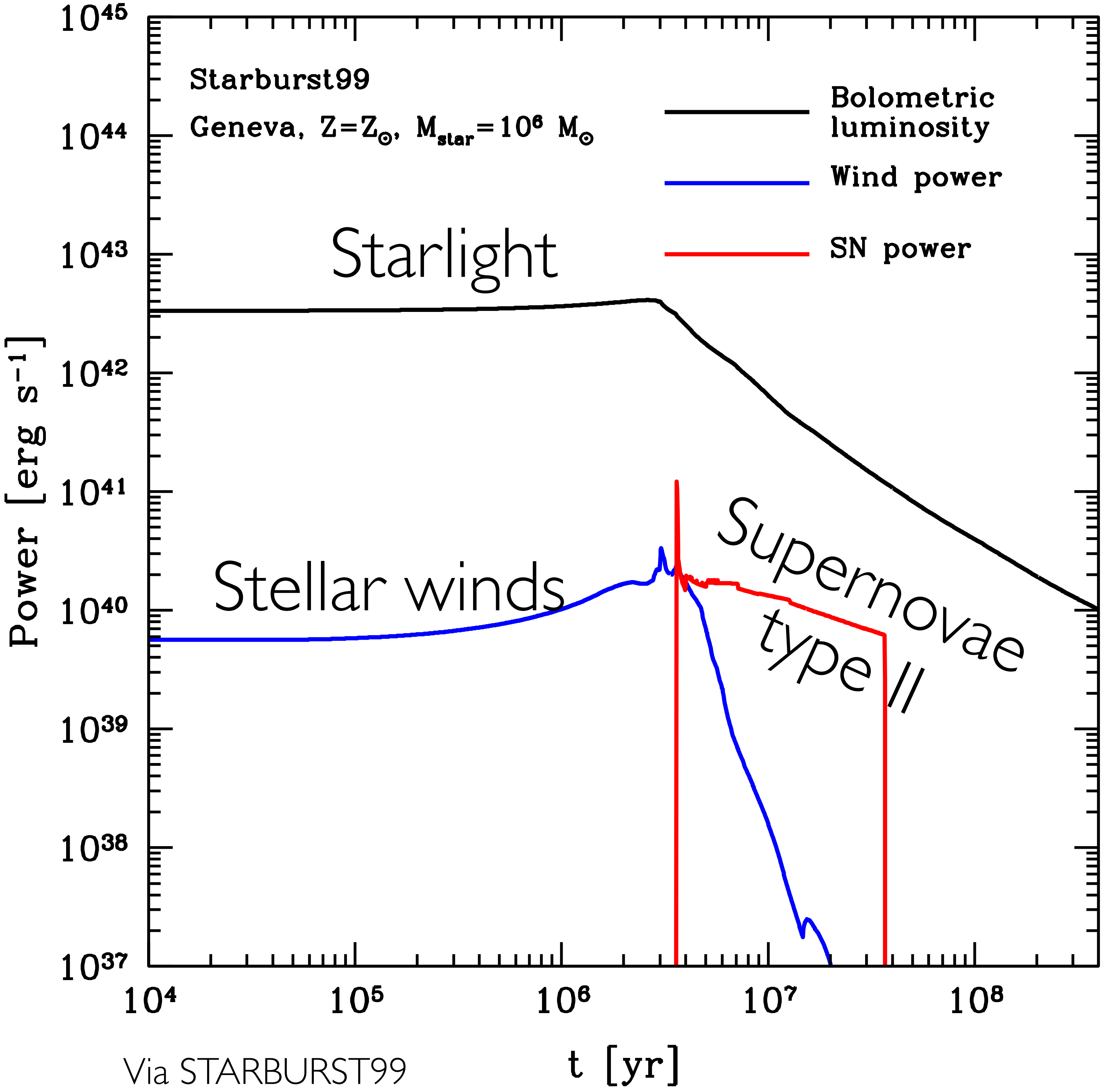
$$M_{\rm cl} \approx 10^4\, M_\odot$$
$$r_{\rm GMC} \approx 50\,{\rm pc}$$

- Westerlund 2 is less than 2 Myr old. No supernovae has exploded (the first supernova explodes after ~4 Myr).
- At his point, the HII region has already destroyed the molecular cloud.

Credit: X-ray; Y.Nazé, G.Rauw, J.Manfroid (Université de Liège), CXC, NASA
Infrared; E.Churchwell (University of Wisconsin), JPL, Caltech, NASA

The stellar feedback in star forming regions

Agertz et al. (2013)



Via STARBURST99
(Leitherer et al. 1999)

- Massive stars ($M>8\ M_{sun}$) live for only a few Myr
- They output copious amounts of energy is star light. Some of it ionizes the gas, but does not heat the gas beyond 10^4 K
- Stellar winds are launched from the envelope of massive stars
- Core-collapse supernovae type II is the end stage of stellar evolution for these stars.
- In terms of energy coupling to the local interstellar medium, it is SNe that dominate

The NFW density profile

Navarro-Frenk-White

$$\rho(r) = \frac{\rho_0}{(r/r_s)(1+r/r_s)^2}$$

where $r_\mathrm{s} = r_{200}/c$

Virial radius r_{200} is defined as the radius where the mean interior density is $\Delta_\mathrm{c}\rho_\mathrm{crit}$

A common definition is $\Delta_\mathrm{c} = 200$

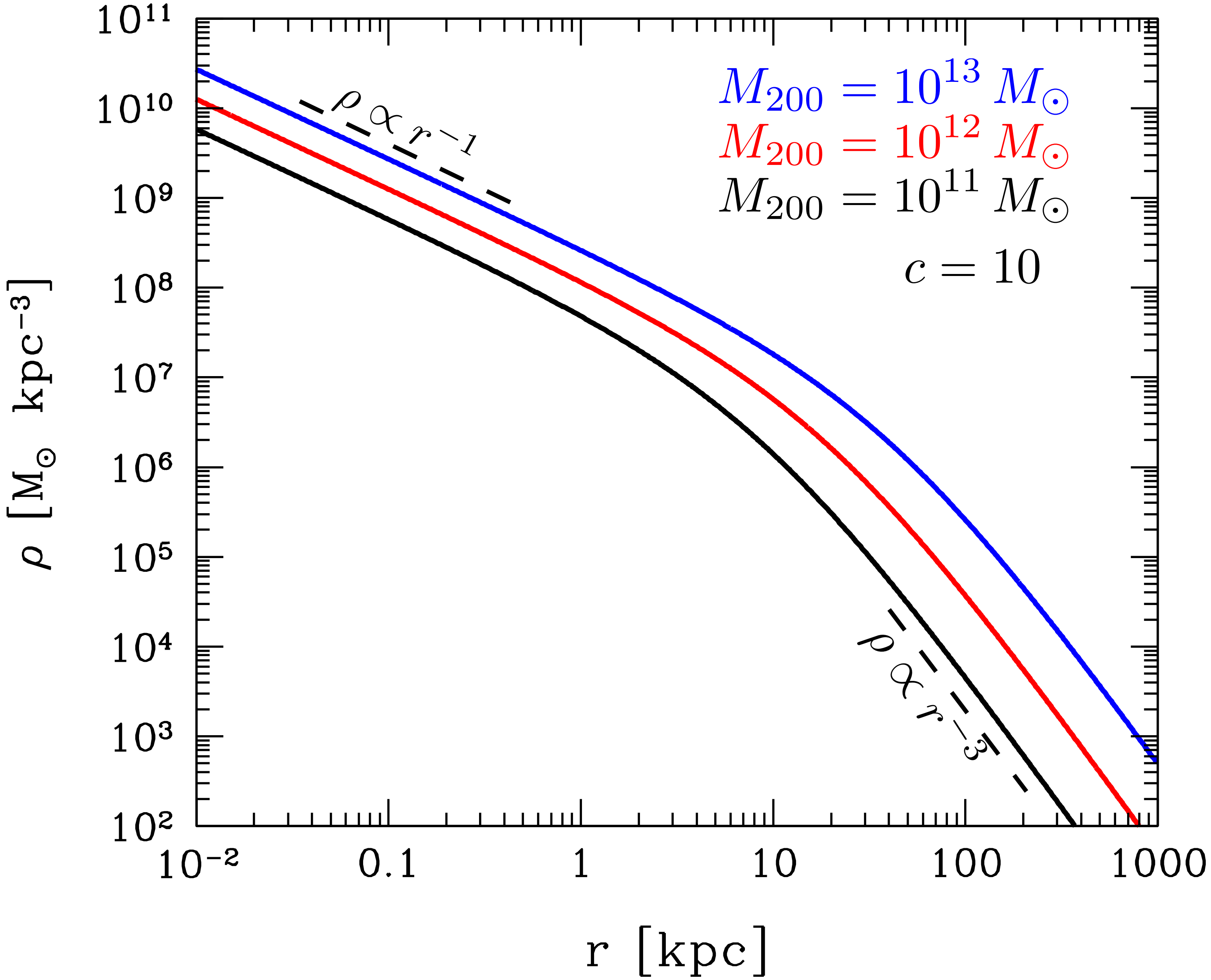
$\longrightarrow$ Virial mass $M_{200} = 200\rho_\mathrm{crit}4\pi r_{200}^3/3$

$$\longrightarrow \quad \rho_0 = \frac{\Delta_\mathrm{c}\rho_\mathrm{crit}}{3}\frac{c^3}{[\ln(1+c)] - c/(1+c)]}$$

Profile completely defined via 2 parameters, for example: M_{200} and c

Navarro-Frenk-White density profile: examples

$$\rho(r) = \frac{\rho_0}{(r/r_s)(1 + r/r_s)^2} \qquad r_{\rm s} = r_{200}/c$$



Can supernovae do the job?

Ejection: Imagine ejecting a mass m$_{\rm ej}$ from the center of a NFW halo

Energy required for ejection: $E_{\rm ej} = \frac{1}{2} m_{\rm ej} v_{\rm esc}^2$ with, for an NFW halo, $v_{\rm esc} \approx \sqrt{6c} v_{vir}$

$$\longrightarrow \quad E_{\rm ej} = 3c\, m_{\rm ej} v_{\rm vir}^2$$

Energy available for feedback: $E_{\rm fb} = \epsilon_{\rm SN} \chi m_\star E_{\rm SN}$

with $\epsilon_{\rm SN} \leq 1$ $\quad \chi \sim 0.01\, M_\odot^{-1}$ $\quad E_{\rm SN} \approx 10^{51}\,{\rm erg}$

fraction of energy coupling to the ISM

number of SNe per solar mass formed

energy per SN

$$\xrightarrow{E_{\rm ej} = E_{\rm fb}} \quad \frac{M_{\rm ej}}{M_\star} \approx 0.4 \epsilon_{\rm SN} \left(\frac{c}{10}\right)^{-1} \left(\frac{v_{\rm vir}}{200\ {\rm km/s}}\right)^{-2}$$

Hence, even if 100% of the SN energy can be converted into kinetic energy of a galactic wind, SN can only eject about 40% of the stellar mass from a MW-sized halo.

Can supernovae do the job?

Reheating Imagine reheating a mass m$_{gas}$ to the vital temperature of the halo

Internal energy of the gas:

$$E_{\rm int} = \frac{3}{2} m_{\rm gas} \frac{k_{\rm b} T}{\mu m_{\rm p}}$$

Virial temperature of the halo

$$T_{\rm vir} = \frac{\mu m_{\rm p}}{2 k_{\rm b}} v_{\rm vir}^2$$

with a typical galactic ISM temperature

$$T_{\rm init} = 10^4 \ {\rm K}$$

$$E_{\rm reheat} = \frac{3}{2} m_{\rm gas} \frac{k_{\rm b}(T_{\rm vir} - T_{\rm init})}{\mu m_{\rm p}} = \frac{3}{4} m_{\rm gas} v_{\rm vir}^2 \left(1 - \frac{T_{\rm init}}{T_{\rm vir}}\right)$$

Energy available for feedback:

$$E_{\rm fb} = \epsilon_{\rm SN} \chi m_\star E_{\rm SN}$$

$$\longrightarrow \quad \frac{m_{\rm gas}}{m_\star} \approx 17 \epsilon_{\rm SN} \left(\frac{v_{\rm vir}}{200 \ {\rm km/s}}\right)^{-2} \left(1 - \frac{T_{\rm init}}{T_{\rm vir}}\right)^{-1}$$

Hence, in a MW halo (200 km/s), SNe can reheat 17 solar masses of gas for every solar mass formed. Reheating is much more efficient than ejecting gas

Biggest uncertainty is the coupling efficiency

Energy available for feedback: $E_{\rm fb} = \epsilon_{\rm SN} \chi m_\star E_{\rm SN}$

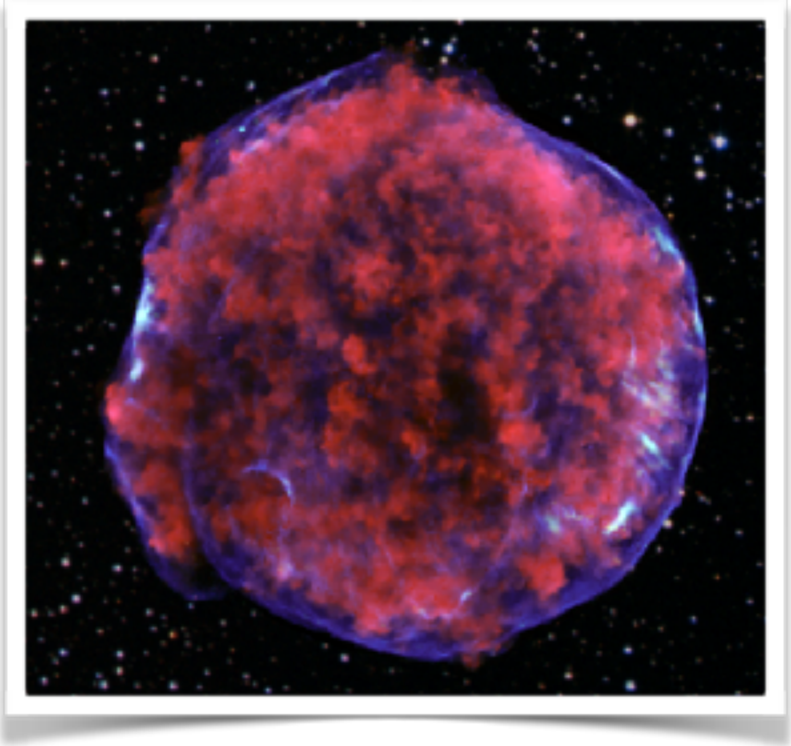
$E_{\rm SN} \approx 10^{51}\,{\rm erg}$

with $\epsilon_{\rm SN} \leq 1$

fraction of energy coupling to the ISM

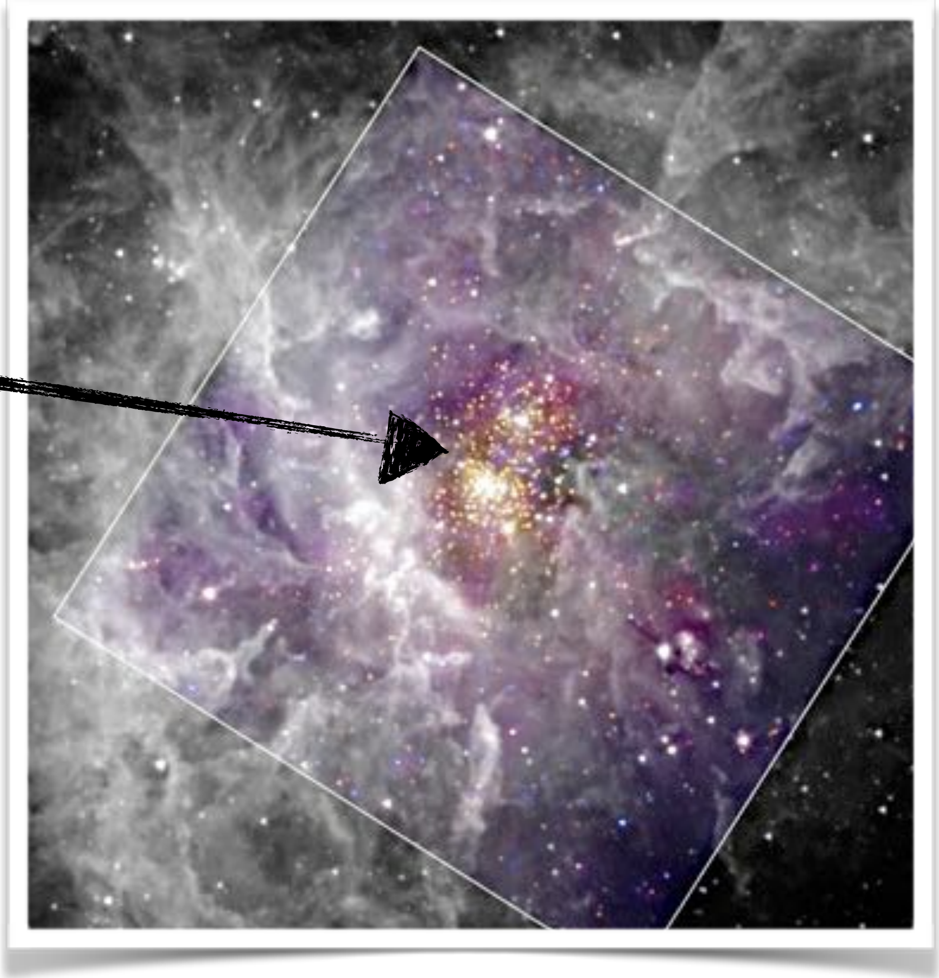
~80-90% of initial energy is likely radiated away in the first few 10,000 year after the explosion

(e.g. Thornton et al 1998)

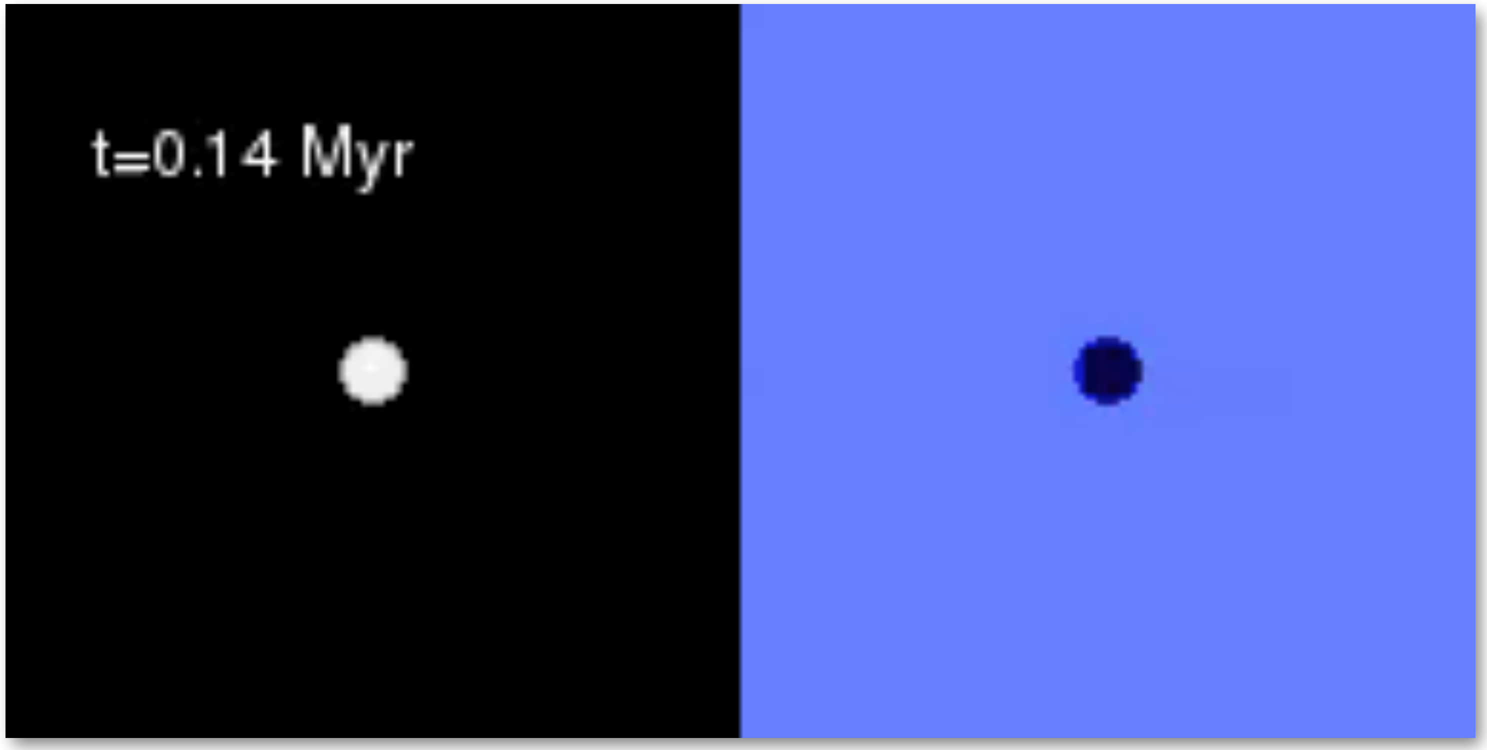


But SNe are clustered. Superbubbles!

- In reality, stars form in clusters and it is the effective of many, possible 1000s of SNe that reheat the gas leading to gas escaping the galaxy as a wind.



- Test of supernovae explosions from a star cluster of mass 10^6 M_{sun}



density

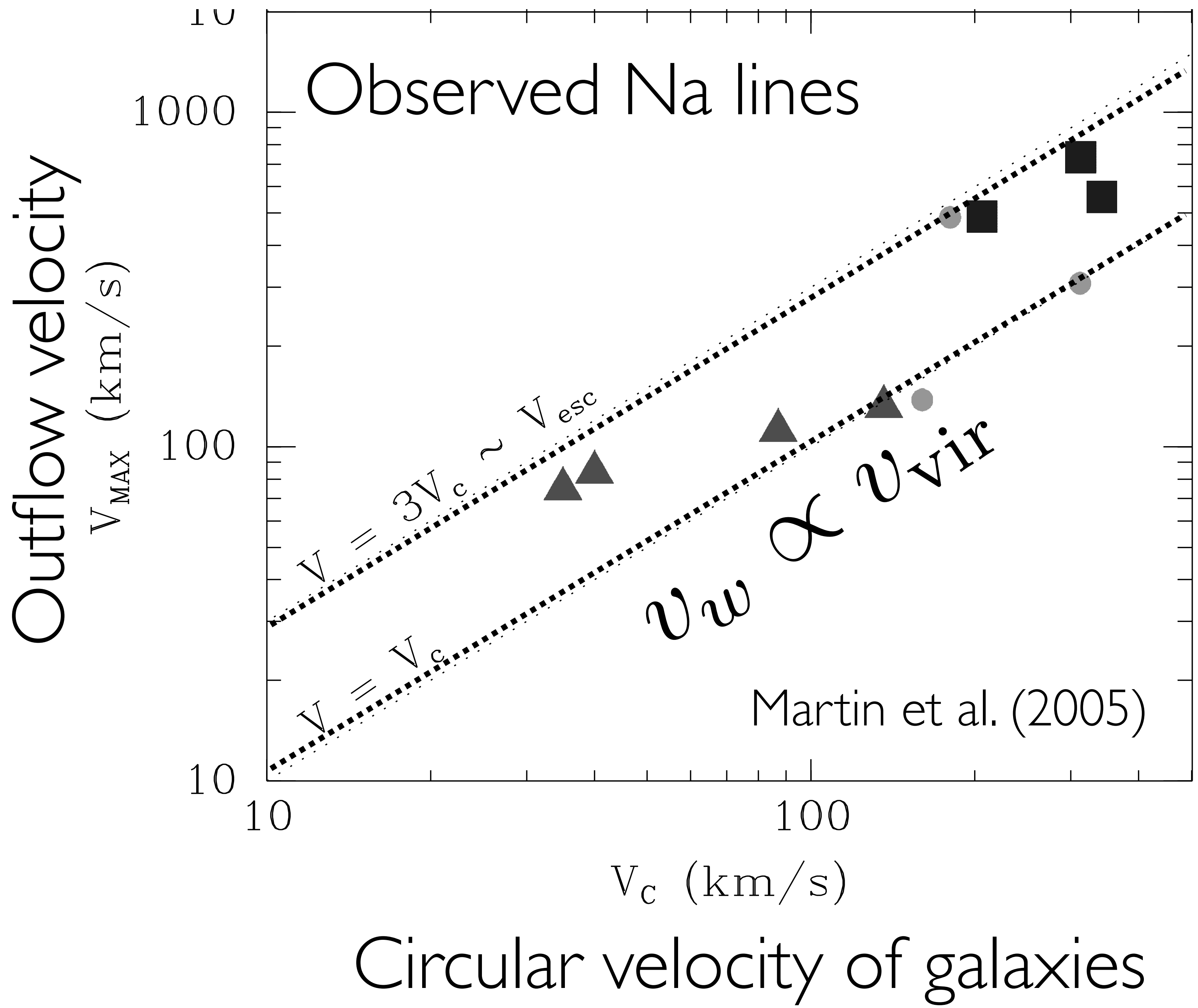
temperature

1kpc

Observed properties of galactic winds: velocity

- Outflow velocities of the gas is often observed from the Doppler shift in some absorption line
- Galaxies featuring galactic winds feature wind velocities close to the escape velocity of the galaxy!

$$v_w \propto v_{\rm vir}$$



How much mass is entrained in the winds?

What matters for the stellar-mass halo mass relation is how much gas mass is ejected per solar mass of stars formed

Rate at which mass is ejected into the wind from a galaxy via SNe feedback: $\dot{m}_{\mathrm{w}}$

Star formation rate: $\dot{m}_{\star}$

Mass loading factor: $\eta \equiv \dot{m}_{\mathrm{w}} / \dot{m}_{\star}$

Due to the complex interactions between different astrophysical scales, we do not yet have a theoretical understanding of how winds emerge.

Two regimes are usually considered in term of mass loading: **energy and momentum driving**

Energy driven winds

Energy-driving of winds: $\dot{E}_w = \frac{1}{2}\dot{m}_w v_w^2$

Feedback input rate: $\dot{E}_{\rm fb} = \epsilon_{\rm SN}\chi\dot{m}_\star E_{\rm SN}$

Assuming $v_w \propto v_{\bf vir}$ and $\dot{E}_w = \dot{E}_{\rm fb}$

yields a mass loading $\eta \equiv \dot{m}_{\rm w}/\dot{m}_\star$

$$\longrightarrow \eta = \eta_0 \left(\frac{v_{\rm vir}}{200 \ {\rm km/s}}\right)^{-2}$$

This particular wind-model is used abundantly in (semi)-analytical models of galaxy formation. In order for these models to have a sufficiently strong impact on the galaxy stellar mass function (i.e., strong suppression of galaxy formation in low mass haloes), the models typically require $\varepsilon_{\rm SN} \sim 1$

Momentum driven winds

Momentum is conserved $\dot{m}_w v_w \propto \dot{m}_\star$

momentum injection rate is proportional to the star formation rate

Assuming $v_w \propto v_{\rm vir}$

Yields $\eta \equiv \dot{m}_{\rm w}/\dot{m}_\star$

$$\longrightarrow \quad \eta = \eta_0 \left(\frac{v_{\rm vir}}{200 \ {\rm km/s}} \right)^{-1}$$

This model describes momentum driven feedback well, for example radiation pressure. It would also describe supernovae driven winds well, if most of the energy is radiated away and only momentum is conserved!

Confronting simple models with observations

Consider the **integrated** mass loading over time

$$\eta \equiv \dot{m}_{\mathrm{w}}/\dot{m}_{\star} \quad \longrightarrow \quad \eta = m_{\mathrm{w}}/m_{\star}$$

Assume **galactic baryon mass** + mass in wind = the cosmic baryon fraction

$$m_{\mathrm{b}} + m_{\mathrm{w}} = f_b m_{\mathrm{vir}}$$

with $m_{\star} = f_{\star} m_{\mathrm{b}}$

yields $m_{\mathrm{b}} = \dfrac{f_{\mathrm{b}} m_{\mathrm{vir}}}{1 + \eta f_{\star}}$ ⟵ Handy fitting formula for observations

with

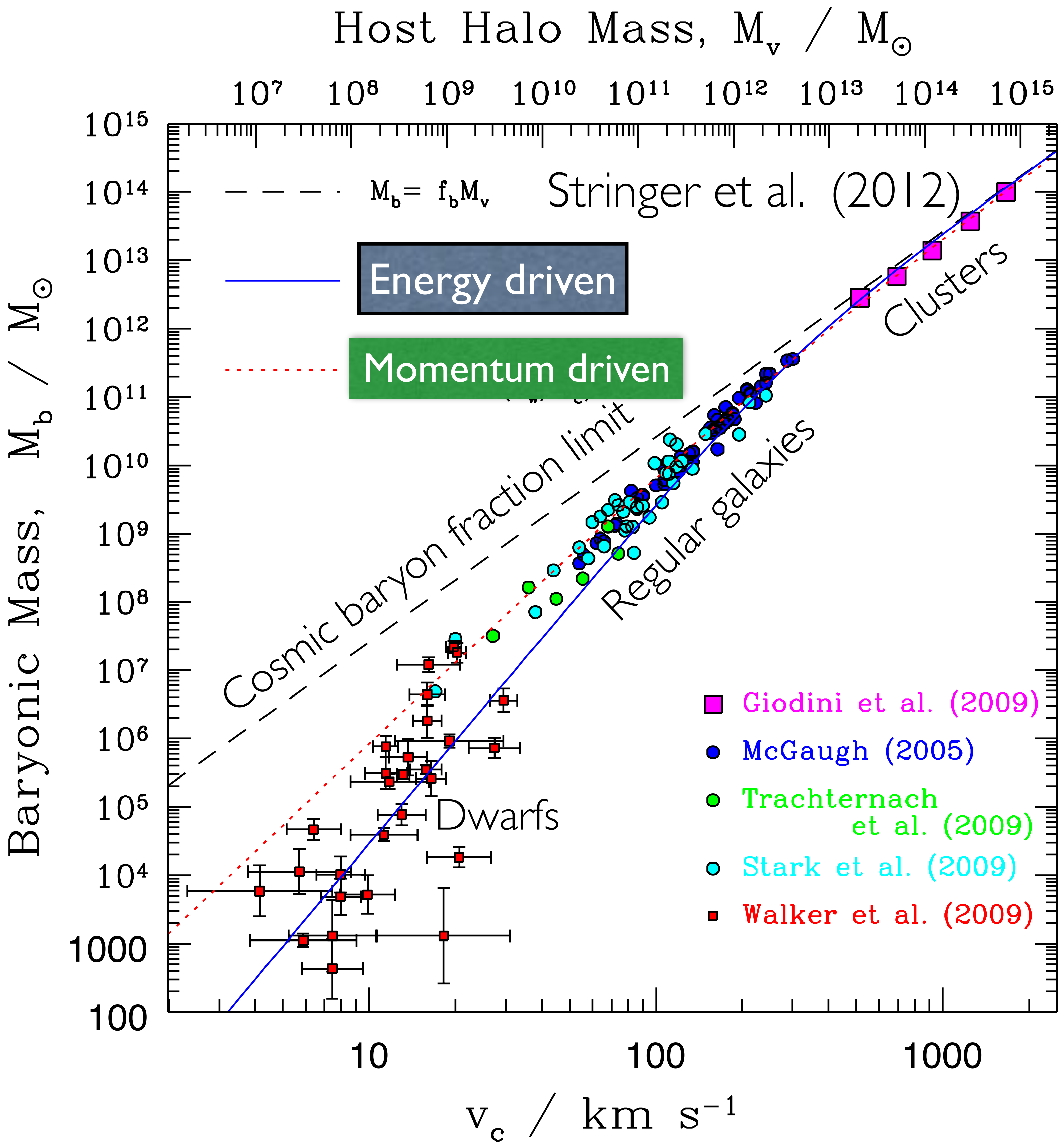
Energy driven:

$$\eta = \eta_0 \left(\frac{v_{\mathrm{vir}}}{200\ \mathrm{km/s}} \right)^{-2}$$

Momentum driven:

$$\eta = \eta_0 \left(\frac{v_{\mathrm{vir}}}{200\ \mathrm{km/s}} \right)^{-1}$$

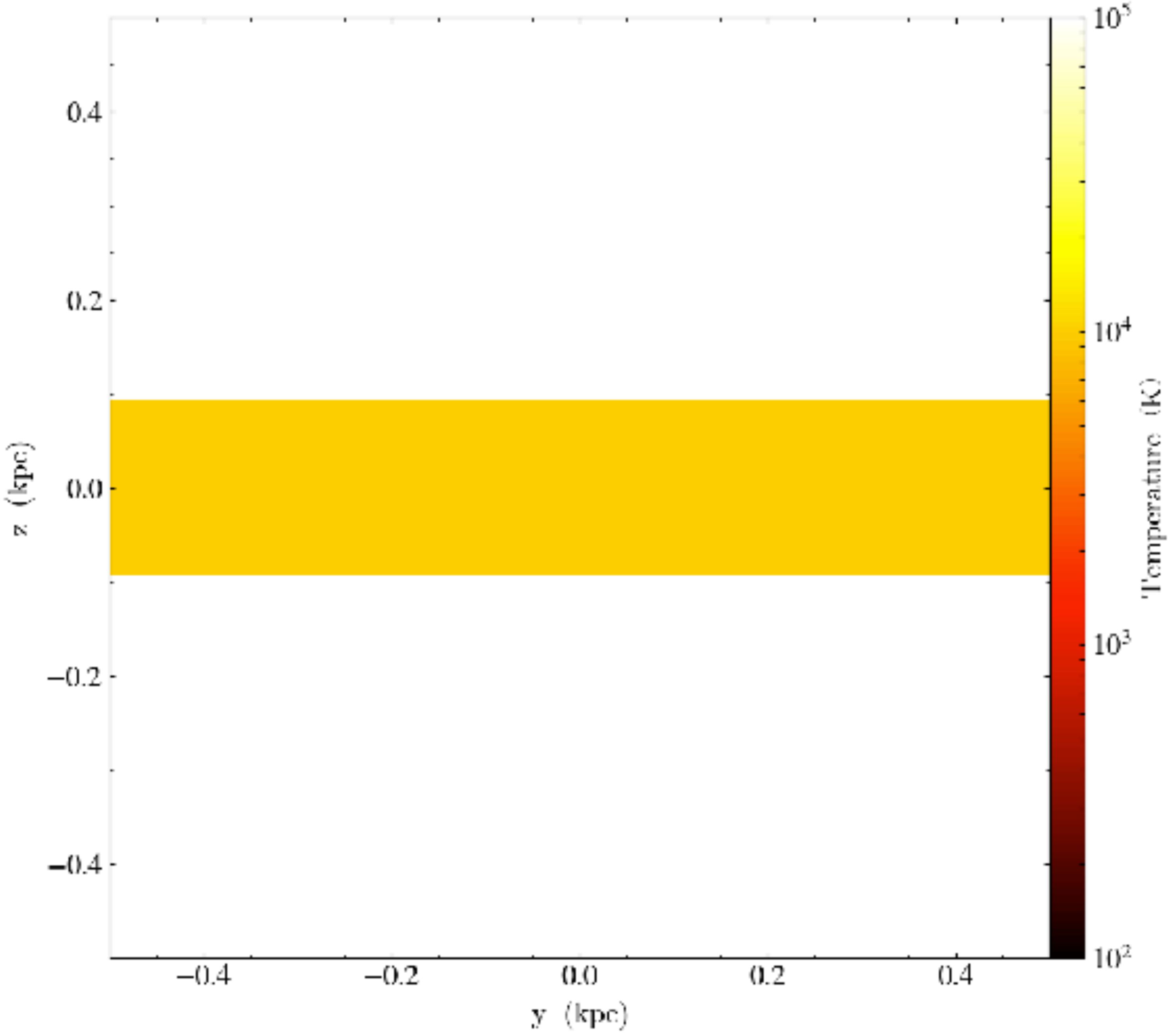
Confronting simple models with observations



- Data points are total baryon masses (stars+all observed gas)
- In cluster, all baryons are accounted for!
- Low mass galaxies are missing most of their cosmic baryons.
- Energy driven winds (supernovae) can in principle explain this.

The lab

- 3D simulation in a 1 kpc^3 box of a gas slab in an NFW dark matter halo potential.
- The halo's force acts only in the z-direction.
- The gas slab is representative of a patch of a disc galaxy, and stars form at high gas densities and inject energy from SNe, leading to galactic fountains and/or winds.
- Energy is injected immediately when stars form. In reality, a single stellar population will feature type II SN for almost 40 Myr, the lifetime of 8 Msun stars.
- You will run the simulation for at most ~100 Myr, which is sufficient to get an understanding of whether winds develop.



The lab

Prerequisites:

You will need the following tools:

- git for downloading of material and code
- `gfortran` or another Fortran compiler for compiling RAMSES
- The `RAMSES` code for running your simulations
- `python` and `YT` for data analysis

`git`, `gfortran`, `python and YT` should all be installed as part of your system installation your laptop. Follow the instructions on the homepage:

https://indico.nbi.ku.dk/internalPage.py?pageId=9&confId=933

The lab

`blowout (patch) —> ramses3d`

`boom.nml: namelist for the exercise`

`flux.py: Python/YT script for outflow properties`

`images.py: density and temperature images`

```
gravity_params=1.e2,1e4,0.5,2e6,0.2,1.0d10,10.0
```

The lab

`boom.nml: namelist for the exercise`

```
gravity_params=Sigma1,T1,Sigma2,T2,z_disc,M200
```

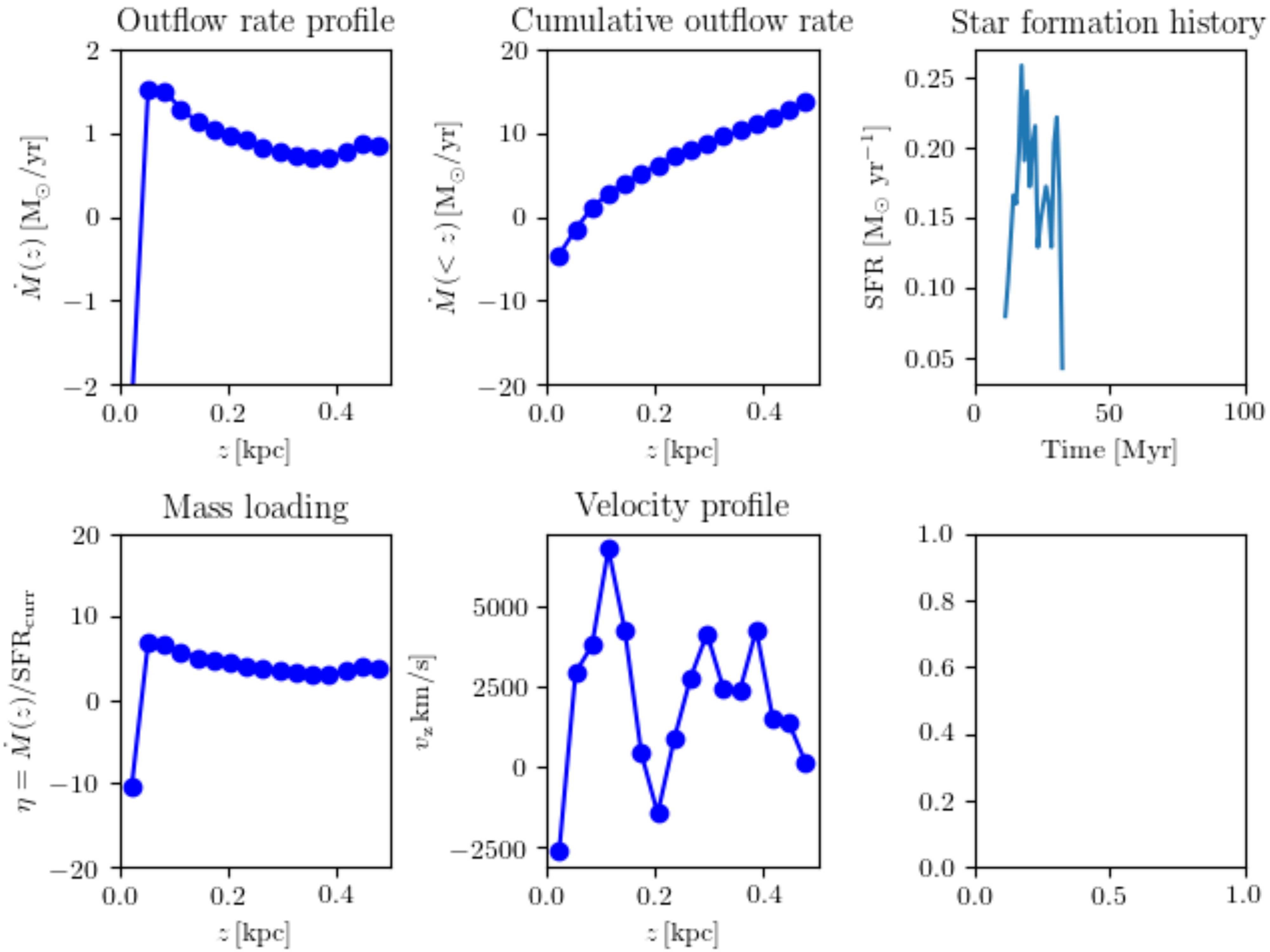
where

- `Sigma1`= initial surface density of the slab [Msun/pc^2]
- `T1`= initial gas temperature of the slab [Kelvin]
- `Sigma2`= initial surface density of the surrounding medium [Msun/pc^2]
- `T2`= initial gas temperature of the surrounding medium [Kelvin]
- `z_disc`= slab thickness [kpc]
- `M200`= dark matter halo virial mass [Msun]

By default it is set to:

```
gravity_params=1.e2,1e4,0.5,2e6,0.2,1.0d10
```

The lab


Outflow rate profile
2
1
0
−1
−2
$\dot{M}(z)$ [M$_\odot$/yr]
0.0
0.2
0.4
z [kpc]
Cumulative outflow rate
20
10
0
−10
−20
$\dot{M}(<z)$ [M$_\odot$/yr]
0.0
0.2
0.4
z [kpc]
Star formation history
0.25
0.20
0.15
0.10
0.05
SFR [M$_\odot$ yr^{-1}]
0
50
100
Time [Myr]
Mass loading
20
10
0
−10
−20
$\eta = \dot{M}(z)/\mathrm{SFR_{curr}}$
0.0
0.2
0.4
z [kpc]
Velocity profile
5000
2500
0
−2500
v_z km/s
0.0
0.2
0.4
z [kpc]
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.5
1.0

The lab

Q1. Outflows properties vs halo mass

Q2. Regulation of star formation

Q3. Energy or momentum driven winds? Or none of these?

Q4. (Time permitting) Sensitivity to numerical resolution

Q5. (Time permitting) Sensitivity to star formation parameters